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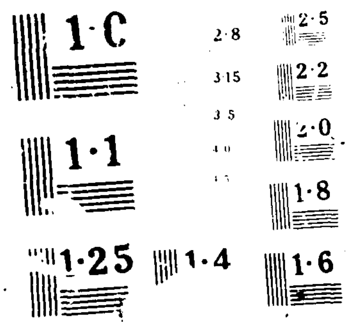
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TECHNICAL REPORT ARCCB-TR-87027

EFFECT OF ROTATION ON THE LATERAL STABILITY OF A FREE-FLYING COLUMN SUBJECTED TO AN AXIAL THRUST WITH DIRECTIONAL CONTROL

AD-A188 690

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OCTOBER 1987

US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER

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This report discusses some aspects of the stability problems of a free-flying column subjected to axial thrusts. In an age of spacecrafts and missiles, the stability of unsupported flying structures is obviously of great importance. Surprisingly though, there has not been a great deal of work addressing this type of problem. In this report, first the brief history of the lateral stability of a column is reviewed, and then the basic characteristic features of the stability problem of a free-free column are described. The mathematical
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20. ABSTRACT (CONT'D)

techniques developed to solve these problems depend on a particular problem considered. The most general case requires the solution of a nonself-adjoint differential equation/boundary condition system, which is homogeneous and with zero eigenvalues. Numerical procedures for such a system appear to work well, although theoretical proof of convergence is still lacking. Results of these procedures are discussed.

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INTRODUCTION

In this report, a long free-free slender beam is used as a model for a flexible missile or rocket. The beam behaves as a Bernoulli-Euler column, and in this case is assumed to be rotating about its longitudinal axis and subject to an end thrust (Figure 1). Of prime interest is the effect of the rotation on the lateral stability of the beam. The motion is assumed to be planar.

Different phases of the problem have been investigated in the past. A summary of the previous work is given in Reference 1. Silverberg (ref 2) was the first to include thrust on the flying column. The differential equation for a free-flying beam was given earlier as shown in Reference 3. Beal (ref 4) and Feodos'ev (ref 5) obtained results with pulsating thrust. In 1972, Matsumoto and Mote (ref 6) treated a similar problem with directional thrust. In this case, however, feedback control was included and a time delay was applied to the control. The next contribution to understanding the problem was given by Peters and Wu (ref 1). They concentrated on mode shape solutions at zero frequency for different thrusts. A comprehensive description is also given in Reference 1 for the eigenvalues and mode shape near zero thrust and with a thrust direction close to that of a follower force. Recently, Park and Mote (ref 7) included a concentrated mass and feedback control. The feedback control included was allowed to be from different points along the beam.

As stated above, this report assesses the effect of rotation on the stability of a free-free beam. The following section is a description of the problem. Then the variational statement used for the solution is described. Next we show how the variational statement is used with finite elements to solve the problem, and lastly, we discuss the results of our investigation.

References are listed at the end of this report.

PROBLEM STATEMENT

The geometry of the problem is shown in Figure 1. The beam has a constant cross-section of area A, density ρ, Young's modulus E, and moment of inertia I. It shows a free-flying column subject to axial thrust with directional control and rotating about its axis. The differential equation for the beam is given by

$$EIu^{iv} + P\left(\frac{x}{\ell} u'\right)' + \rho A u + \rho A \Omega^2 u = 0 \tag{1}$$

The first three terms represent the column as treated in Reference 1. The last term on the left-hand side shows the effect of the rotation. The boundary conditions are given by

$$u''(0) = 0 \quad , \quad u''(\ell) = 0 \quad , \quad u = \frac{\partial^2 u}{\partial t^2}$$

$$u'''(0) = 0 \quad , \quad EIu'''(\ell) - K_\theta P u'(\ell) = 0 \tag{2}$$

In dimensionless form with

$$\bar{u} = u/\ell \quad , \quad \bar{x} = x/\ell \qquad \tau = t/T$$

$$T^2 = \frac{\rho A \ell^4}{EI} \quad , \quad Q = \frac{P\ell^2}{EI} \quad , \quad \omega = \Omega T \tag{3}$$

and writing

$$\bar{u}(\bar{x},\tau) = \hat{u}(\bar{x})e^{\lambda\tau} \tag{4}$$

the differential equation then becomes

$$\bar{u}'''' + Q(\bar{x}\bar{u}')' + \lambda^2 \hat{u} + \omega^2 \hat{u} = 0 \tag{5}$$

with the boundary conditions

$$\bar{u}''(0) = 0$$

$$\bar{u}'''(0) = 0$$

$$\bar{u}''(1) = 0$$

$$\bar{u}'''(1) - K_\theta Q[\bar{u}'(1)] = 0 \tag{6}$$

Rewriting Eq. (5) as (and dropping hats)

$$u'''' + Q(xu')' + (\lambda^2+\omega^2)u = 0 \tag{7}$$

It appears that the addition of rotation simply shifts the frequency of vibration of the system. The boundary conditions, Eq. (6), become

$$u''(0) = 0$$

$$u'''(0) = 0$$

$$u''(1) = 0$$

$$u'''(1) - K_\theta Q u'(1) = 0 \tag{8}$$

The spacial variables are made dimensionless by dividing through by the beam's length ℓ and time is made dimensionless by dividing through by a constant $T = (\rho A \ell^4 / EI)^{1/2}$ which has the units of time.

The parameter λ is a complex number in general

$$\lambda = \lambda_R + i\lambda_I$$

where both λ_R and λ_I are real numbers.

VARIATIONAL STATEMENT

To find the form of the variational statement, the differential equation is multiplied by an arbitrary variation of the adjoint field variable, $\delta v(x)$, and integrated over the beam length. Integration-by-parts indicates the form of the variational statement and the natural boundary conditions. The variational statement is given by

$$\delta J = 0 \tag{9}$$

where

$$J = \int_0^1 [u''v'' - Qxu'v' + (\lambda^2+\omega^2)uv]dx + Q(1+K_\theta)u'(1)v(1) \tag{10}$$

Performing the variation of J with respect to u and v, one can arrive at the original boundary value problem as well as the adjoint. Equation (10) is the basis for a finite element solution to the described problem.

FINITE ELEMENT AND NUMERICAL FORMULATION

The procedure begins by taking the variation of Eq. (10) and allowing the variations in the problem variable, $\delta u(x)$, to be zero, i.e., varying adjoint variable $v(x)$ only for now,

$$\int_0^1 [u''\delta v'' - Qxu'\delta v' + \Lambda^2 u\delta v]dx - Q(1+K_\theta)u'(1)\delta v(1) = 0 \tag{11}$$

where $\Lambda^2 = \lambda^2 + \omega^2$. To discretize, the beam is divided into L elements, letting

$$\xi = L\{x - \frac{i-1}{L}\} \qquad i = 1,2,3...,L \tag{12}$$

be the running coordinate in each element. Substituting Eq. (12) into Eq. (11)

$$\sum_{i=1}^{L} \int_0^1 [L^3 i^{(i)''}\delta v^{(i)''} - Q\{\xi + (i-1)\}u^{(i)'}\delta v^{(i)'} + \frac{\Lambda^2}{L} u^{(i)}\delta v^{(i)}]ds$$
$$- Q(1+K_\theta)u^{(L)'}(1)\delta v^{(L)}(1) = 0 \tag{13}$$

In order that the displacements and their derivatives within an element be expressed in terms of their nodal values, the coordinate vectors are introduced.

$$\bar{U}^{(i)T} = \{U_1^{(i)} \quad U_2^{(i)} \quad U_3^{(i)} \quad U_4^{(i)}\}$$
$$\bar{V}^{(i)T} = \{V_1^{(i)} \quad V_2^{(i)} \quad V_3^{(i)} \quad V_4^{(i)}\} \tag{14}$$

$U_1^{(i)}$, $U_2^{(i)}$ represent the displacement and slope at the left end of the ith element, and $U_3^{(i)}$ and $U_4^{(i)}$ represent deflection and slope at the right end. A similar interpretation is applied to the adjoint coordinate vector $\bar{V}^{(i)}$. The transform is indicated by T.

Hermitian polynomials are used to relate the displacements within an element to its nodal values, hence, the following shape function is assumed:

$$\bar{a}^T(\xi) = \{1 - 3\xi^2 + 2\xi^3 \ , \ \xi - 2\xi^2 + \xi^3 \ , \ 3\xi^2 - 2\xi^3 \ , \ -\xi^2 + \xi^3\} \tag{15}$$

so that

$$u^{(i)}(\xi) = \bar{a}^T(\xi)\bar{U}^{(i)}$$

$$v^{(i)}(\xi) = \bar{a}^T(\xi)\bar{V}^{(i)} \tag{16}$$

Substituting Eq. (16) into Eq. (13)

$$\sum_{i=1}^{L} \bar{U}^{(i)T}\{L^3\bar{C} - Q[\bar{D}+(i-1)\bar{B}] + \frac{\Lambda^2}{L}\bar{A}\}\delta\bar{V}^{(i)} - Q[1+K_\theta]\bar{U}^{(L)T}\bar{E}\delta\bar{V}^{(L)} = 0 \tag{17}$$

with

$$\bar{A} = \int_0^1 \bar{a}\bar{a}^T d\xi \quad , \quad \bar{B} = \int_0^1 \bar{a}'\bar{a}'^T d\xi \quad , \quad \bar{C} = \int_0^1 \bar{a}''\bar{a}''^T d\xi$$

$$\bar{D} = \int_0^1 \xi\bar{a}'\bar{a}'^T d\xi \quad , \quad \bar{E} = \bar{a}'(L)\bar{a}^T(L) \tag{18}$$

Rewriting Eq. (17),

$$\sum_{i=1}^{L} \bar{U}^{(i)T}\{\Lambda^2 P^{(i)} + S^{(i)}\}\delta\bar{V}^{(i)} = 0 \tag{19}$$

where

$$P^{(i)} = \bar{A}/L \qquad i = 1,2,\ldots,L$$

$$S^{(i)} = L^3\bar{C} - Q[\bar{D} + (i-1)\bar{B}] \qquad i = 1,2,\ldots,L-1$$

$$S^{(L)} = L^3\bar{C} - Q[\bar{D} + (L-1)\bar{B}] - Q(1+K_\theta)\bar{E} \tag{20}$$

using certain continuity conditions between the element nodal values

$$U_1^{(i)} = U_3^{(i-1)} \qquad V_1^{(i)} = V_3^{(i-1)}$$

$$U_2^{(i)} = U_4^{(i-1)} \qquad V_2^{(i)} = V_4^{(i-1)} \tag{21}$$

One can write

$$\bar{U}^T = \{U_1^{(1)} \; U_2^{(1)} \; U_3^{(1)} \; U_4^{(1)} \; U_3^{(2)} \; U_4^{(2)} \; \ldots\ldots \; U_3^{(L)} \; U_4^{(L)}\}$$

$$\bar{V}^T = \{V_1^{(1)} \; V_2^{(1)} \; V_3^{(1)} \; V_4^{(1)} \; V_3^{(2)} \; V_4^{(2)} \; \ldots\ldots \; V_3^{(L)} \; V_4^{(L)}\} \tag{22}$$

Finally, [P] and [S] are NxN matrices with $N = 2L+2$. Since δv is arbitrary, the eigenvalue problem reduces to

$$\tilde{U}^T\{\Lambda^2[P] + [S]\} = 0 \tag{23}$$

which is solved for the eigenvalues.

CONCLUSIONS AND DISCUSSION

In this report, we have included rotation about the longitudinal axis in the dynamic stability study of a free-flying missile subjected to axial thrusts. It is assumed that the motions of bending and the thrust are in the same plane. In the differential equation, the only difference resulting from the introduction of rotation is a change in the frequency parameter λ^2 to

$$\Lambda^2 = \lambda^2 + \omega^2 \tag{24}$$

where ω is the rotation. Consequently, all the stability curves obtained previously (ref 1) can be used with some simple modifications. It should be noted that in Reference 1, we have written (with $\omega = 0$)

$$\Lambda = \lambda = \lambda_R + i\lambda_I \tag{25}$$

and the stability character of the problem is indicated by: (1) stable vibrations = $\lambda_I \neq 0$, $\lambda_R = 0$; (2) unstable by buckling (divergence) = $\lambda_R \neq 0$, $\lambda_I = 0$; (3) unstable by flutter = $\lambda_R \neq 0$, $\lambda_I \neq 0$; and (4) marginally stable = $\lambda_I = \lambda_R = 0$.

For the present case, the stability behavior is indicated as above, but with Λ_I and Λ_R replacing λ_I and λ_R in the previous stability curves

$$\Lambda = \Lambda_R + i\Lambda_I \tag{26}$$

and

$$\Lambda^2 = (\Lambda_R+i\Lambda_I)^2 = \lambda^2 + \omega^2 = (\lambda_R+i\lambda_I)^2 + \omega^2 \tag{27}$$

or

$$\lambda^2 = (\lambda_R + i\lambda_I)^2 = \Lambda^2 - \omega^2 = (\Lambda_R + i\Lambda_I)^2 - \omega^2 \tag{28}$$

From Eq. (28), when $\Lambda_R = 0$, $\lambda^2 = -\Lambda_I^2 - \omega^2$, hence $\lambda_R = 0$ and $\lambda_I^2 = \Lambda_I^2 + \omega^2$. Thus, originally stable vibrations will remain stable with higher vibration frequency. On the other hand, when $\Lambda_I = 0$, $\lambda^2 = \Lambda_R^2 - \omega^2$, hence $\lambda^2 = \Lambda_R^2 - \omega^2$. Thus, originally divergent motions will become stable vibrations when $\Lambda_R^2 < \omega^2$. In the case of marginal stability $\Lambda = 0$ will certainly be stabilized since $\lambda_I^2 = \omega^2$.

In the case of flutter instability, Eq. (28) states that λ is complex ($\lambda_I \neq 0$, $\lambda_R \neq 0$) if and only if Λ is complex ($\Lambda_I \neq 0$, $\Lambda_R \neq 0$). Therefore, the flutter instability is not affected by the introduction of the rotation, which is an interesting observation.

Several demonstrative stability curves with λ^2 (and Λ^2) versus Q/π^2 are shown in Figures 2 through 5. Only the lowest eigenvalue's branches are shown, since they are the ones which dictate the stability behavior. Figure 2 shows the two lowest stable vibration modes and two rigid body modes on the $\Lambda^2 = 0$ axis. This is the case of a free-flying missile with a follower thrust ($K_\theta = 0$) and with a dimensionless rotation of $\omega^2 = 500$. The two fluxural modes coalesce at load $Q/\pi^2 = 11.18$ beyond which flutter instability begins. The rigid body modes without rotation indicate marginal stability. Due to the rotation ω, the axis is shifted from $\Lambda^2 = 0$ to $\lambda^2 = 0$, therefore, these previously rigid body modes are now stable modes of vibrations. The thrust that is controlled with a small negative tangency ($K_\theta = -0.05$) is shown in Figure 3. It is noted in this figure that the divergence instability without rotation is stabilized by $\omega^2 = 500$. However, the new critical load is lowered from $Q/\pi^2 = 11.18$ to 5.30, not because of ω^2, but due to the negative control parameter K_θ. Figure 4 shows the case of $K_\theta = -1$ or that the thrust has a fixed direction of the inertia axis. It is clear that the divergence instability of the lowest branch is stabilized so that the critical load has been raised from zero to $Q_{CR} = 1.50\ \pi^2$. Finally, the case for a small positive tangency control parameter ($K_\theta = 0.05$) is shown in Figure 5. In this figure, the original divergence instability at $Q/\pi^2 = 3.00$ is stabilized by ω^2. However, the original critical load of flutter instability at $Q/\pi^2 = 9.90$ is not changed by the rotation. Hence, the critical load in this case is raised from 3.00 to 9.90 due to the rotation of $\omega^2 = 500$.

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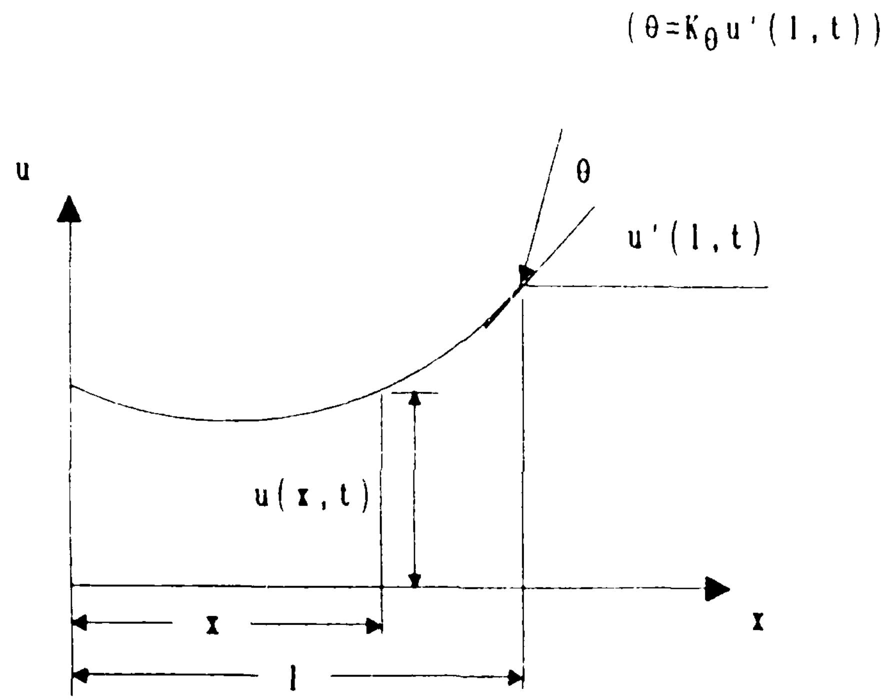

FIGURE 1. GEOMETRY OF THE PROBLEM

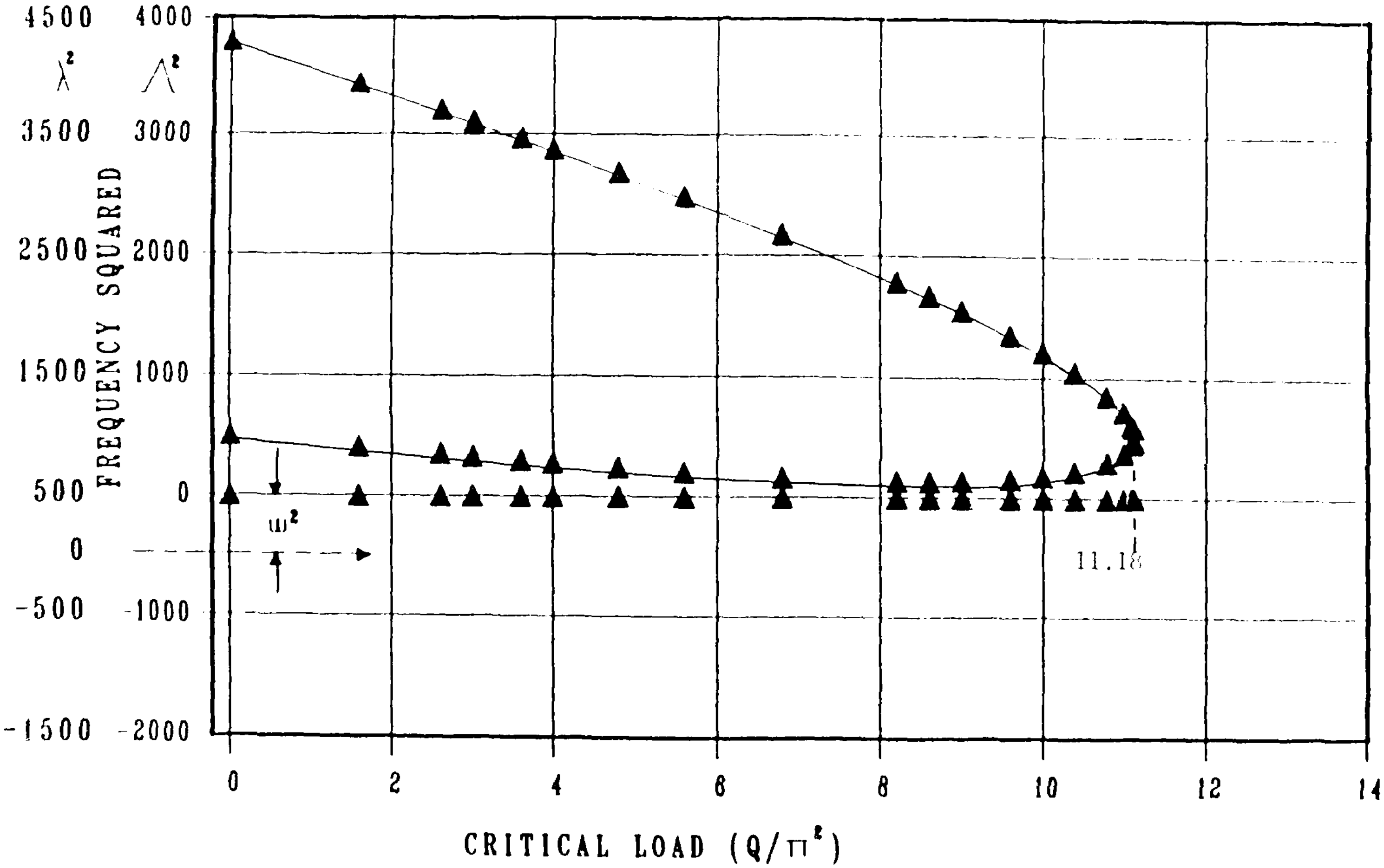

FIGURE 2. CRITICAL LOAD PLOT FOR K_θ= 0.00
(FOLLOWER FORCE)

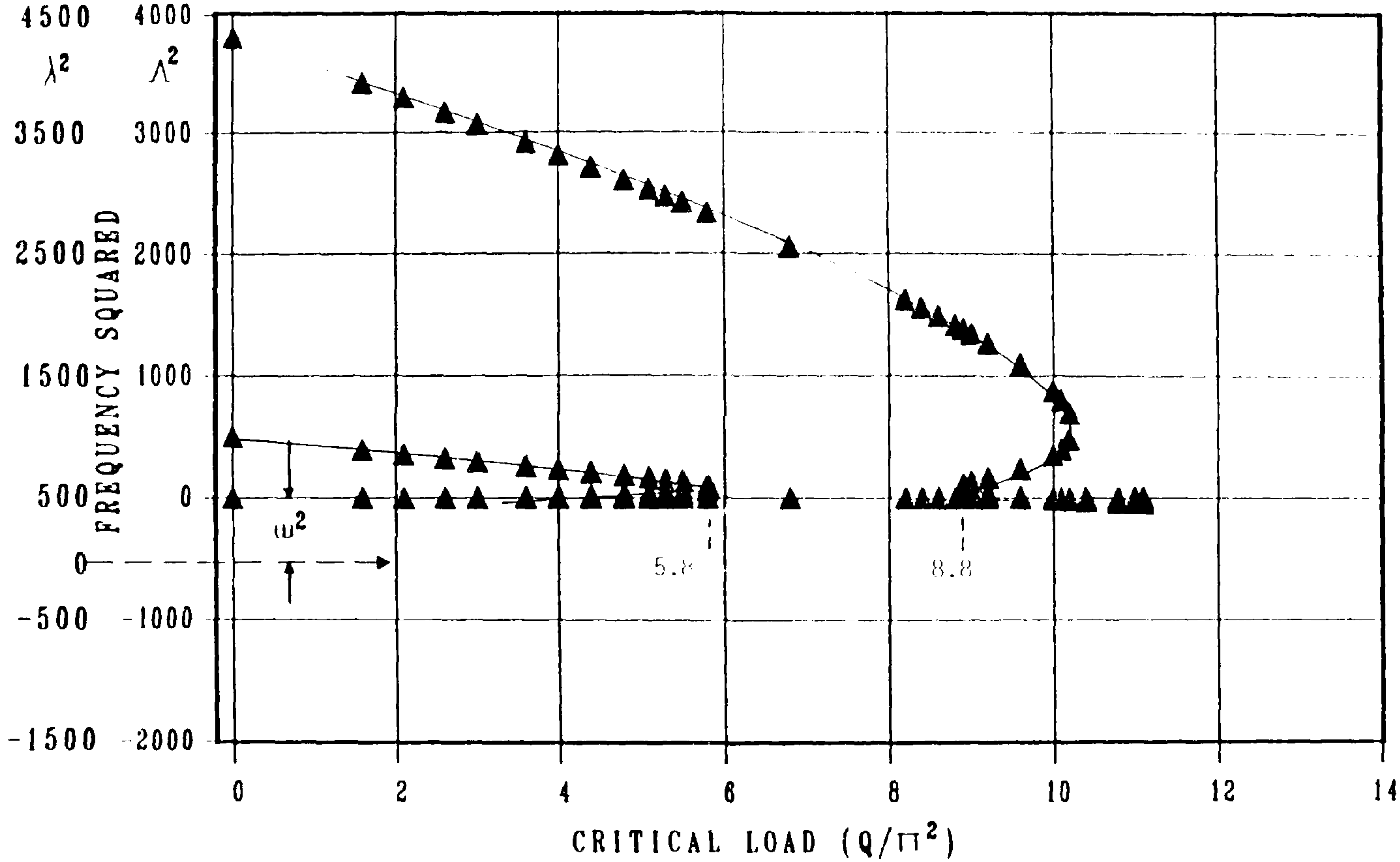

FIGURE 3. CRITICAL LOAD PLOT FOR K_θ= -0.05

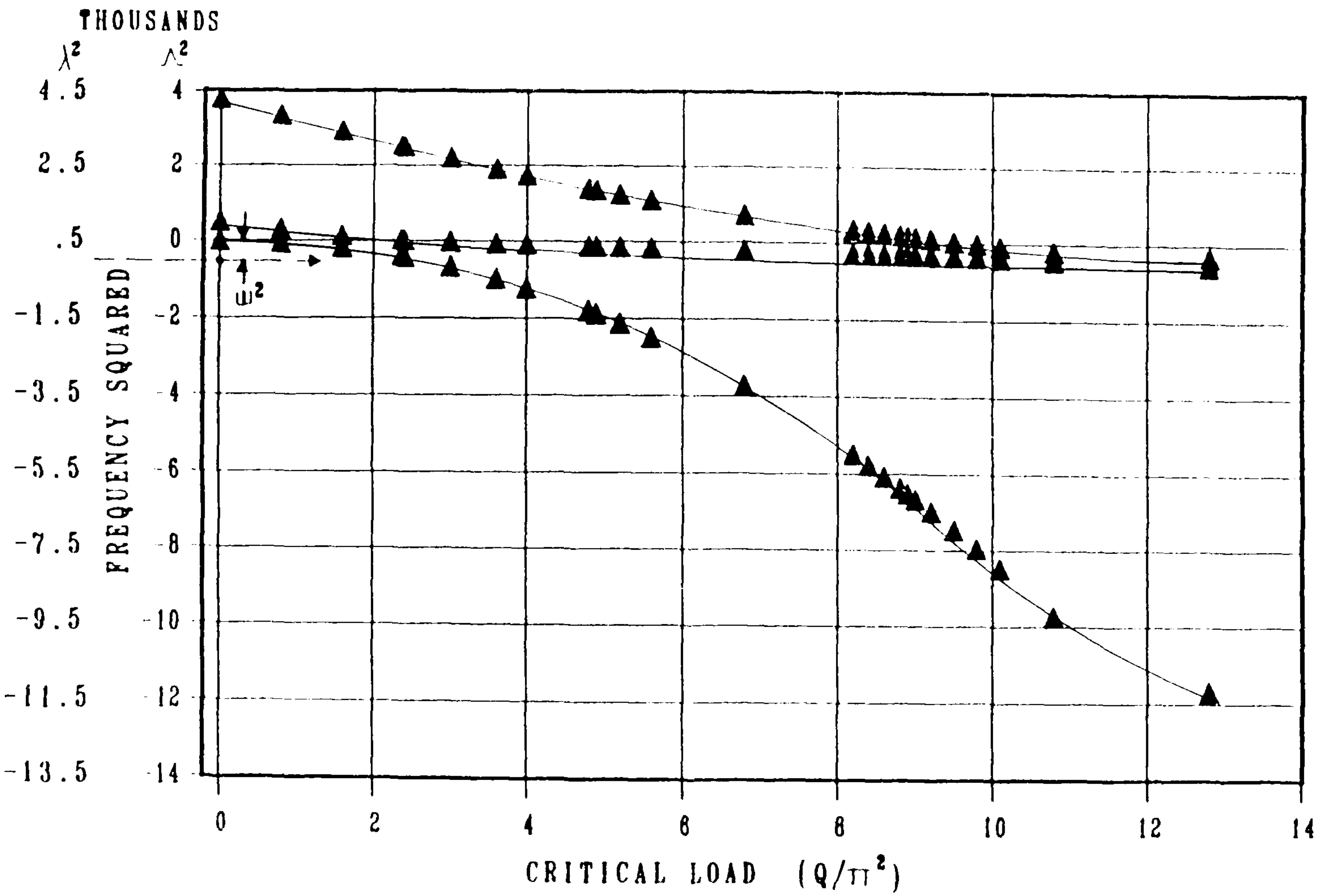

FIGURE 4. CRITICAL LOAD PLOT FOR K_θ = -1.00

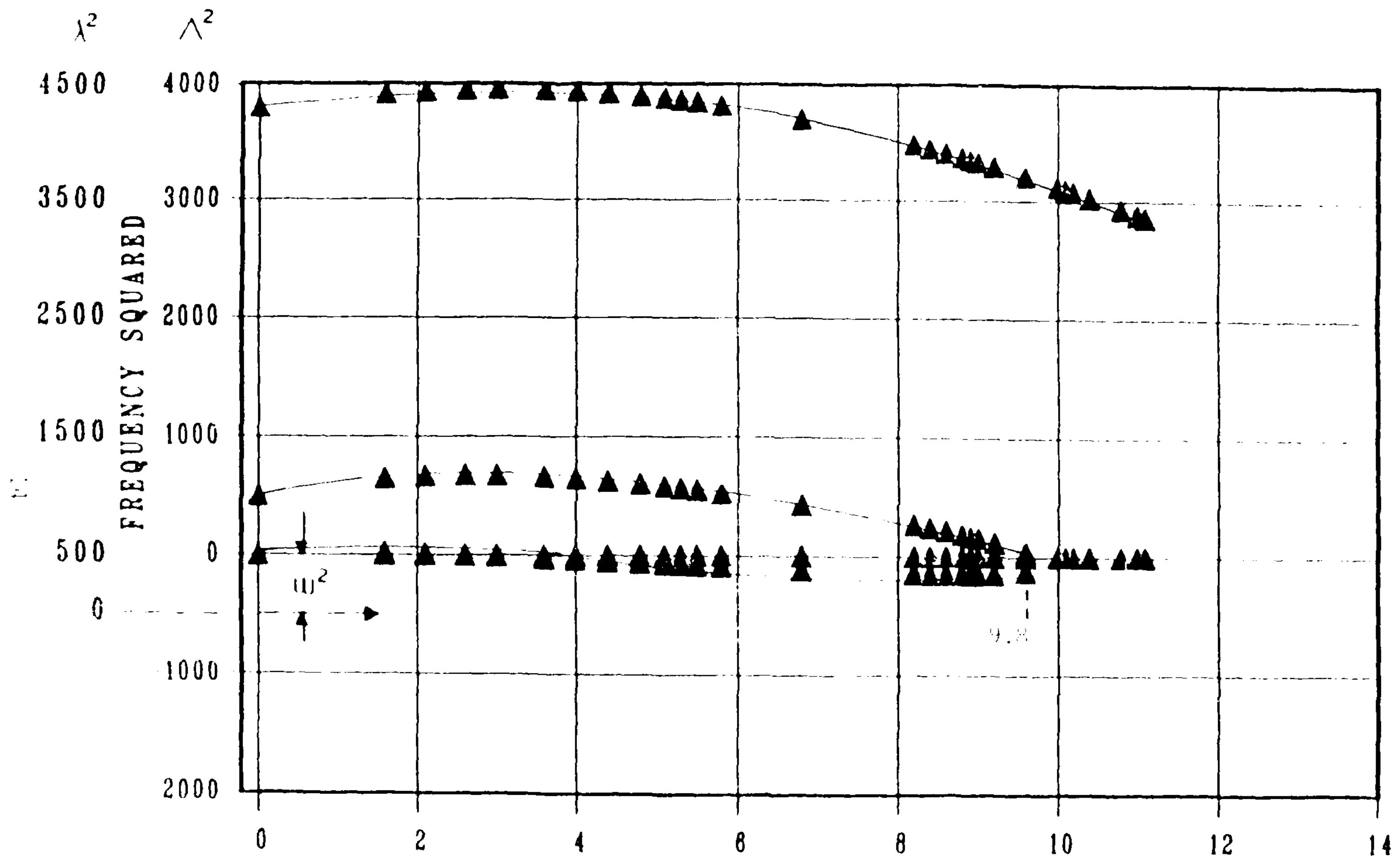

FIGURE 5. CRITICAL LOAD PLOT FOR $K_\theta = 1.00$

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